Virtual Testbeds for Community Resilience Analysis: State-of-the-Art Review, Consensus Study, and Recommendations

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Abstract: As the quantitative hazard research, particularly stemming from the engineering fields, aims to move from component- and building-level modeling into the interdisciplinary space of community-level modeling for resilience, the need to test, verify, and validate community resilience algorithms becomes a critical challenge; *virtual testbeds* are an effective tool for such purposes. We define a virtual testbed as an environment with enough supporting architecture and metadata to be representative of one or more systems such that the testbed can be used to design experiments, examine model or system integration, and test theories. Testbeds enable researchers to assess multidisciplinary integrated community resilience models, thereby helping decision makers to make better community hazard mitigation plans and recovery decisions. This paper leverages the current momentum on using virtual testbeds for community resilience analysis to dissect what testbeds are in practice. To obtain consensus on the presented definition of a testbed, the paper conducted a virtual survey with testbed experts. The survey primarily explored how testbeds have been used across different disciplines, how testbeds differ from case studies, and what are the minimum requirements for a testbed. The paper, then, presents findings from a systematic literature review on 22 identified existing community resilience testbeds and 103 associated publications. According to the literature review and survey results, community resilience testbeds should have both a hazard module and a community module that ideally includes physical, social, and economic systems. The literature review concludes with a discussion on the available tools for testbed development, typical challenges testbed developers encounter, and areas for future testbed research. The availability of existing testbeds for reuse by other researchers, standardization of the development and publication process of new testbeds including obtaining, cleaning, and validating the required data, and verification of numerical algorithms are the main detected issues that need to be addressed in future research. **DOI: 10.1061/(ASCE)NH.1527-6996.0000582.**

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Introduction

Virtual testbeds are being developed and used across the community resilience literature to serve the purpose of verification and validation (V&V) (Attary et al. 2019; Ellingwood et al. 2016a; Fereshtehnejad et al. 2021; Loggins et al. 2019; Mazumder et al. 2021; Noori et al. 2017; Park et al. 2019; Shang et al. 2020). Testbeds were first termed in the nuclear power (NP) industry to be used as a means for NP plant process validation (OHara and Wachtel 1995). However, the idea of developing virtual testbeds at the community level dates back to the 1980s when water distribution network designers were striving to optimally size water distribution pipes, although those published works might have been imprecisely termed as a *test case* or *case study* (Walski et al. 1987). Testbeds are an essential part of the development and testing of community resilience algorithms and serve the needs of training and educational purposes as well. Testbeds enable multidisciplinary teams to design, test, integrate, verify, and validate community resilience algorithms and numerical models at different scales and resolutions, which is critical when interdependencies across systems are of interest. V&V of numerical models is an important step in model development enabled by testbeds (Sargent 2010). Validation is the process of determining if a mathematical or computational model of an event represents the actual event with sufficient accuracy. Whereas, verification is the process of determining that the model's implementation accurately represents the developer's conceptual description and specifications of the model (CFDC 1998). As discussed herein, the development and application of virtual testbeds: (1) enables researchers to test their models that predict the performance of interdependent physical, social, and economic systems and their immediate and long-term impacts in an integrated community resilience assessment; and (2) better support risk-informed decision making by communities to optimize public and private investments.

This paper presents findings from a virtual survey administered to *testbed experts* and a systematic literature review on community resilience testbeds. The survey results provide insight on the

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minimum requirements for a testbed and how testbeds differ from case studies. The results also help obtain consensus on the definition of a testbed. Findings from the literature review include metadata for how the identified testbeds have been developed and used. Of note, this paper does not intend to criticize existing testbeds, point out their shortcomings, or rate them, but rather to synthesize their existence given that testbeds are almost always indirectly presented in papers. Finally, the available tools for testbed development, typical challenges testbed developers encounter, and areas of future testbed research are discussed. This review can be used to aid interdisciplinary teams of hazards and disasters researchers in working together on testbeds and in understanding where the state of knowledge is on testbed development.

Testbeds as Real and Imaginary Communities

Communities are defined as places, such as towns, cities, or counties, designated by geopolitical boundaries (NIST 2016). As such, communities are complex systems comprising interconnected social, economic, and physical systems and processes (Daniel et al. 2022; Enderami et al. 2021) and can be very difficult to accurately model. Testbeds can be designed to represent communities, including imaginary or real communities. Being real versus imaginary is different from being virtual or physical. Virtual and physical refer to whether the testbed itself is digitally simulated on a computer network or has a material existence, whereas real and imaginary are terms used to indicate whether the testbed is a representation of a real or hypothetical community. As physical testbeds for community resilience are neither feasible nor ethical, this paper only discusses virtual testbeds. Imaginary testbeds can be entirely fabricated, including all required data. For example, Gotham City was modeled after the fictitious city from the comic Batman to be used for verifying community resilience models (Mahmoud and Chulahwat 2018). Imaginary testbeds may be based on some sort of reality while still not being a perfect representative and accurate model of an existing location. The Centerville testbed is an example of such an imaginary community, which models a typical midsize community using average statistics of several communities in the Midwest United States (Ellingwood et al. 2016a).

Imaginary testbeds are often used when there are significant data limitations, or when the research is intended to be highly generalizable for geographic areas with similar topology, population, and infrastructure (Ellingwood et al. 2016a). Imaginary testbeds are also particularly useful when a team is attempting to understand how their algorithms fit together given that an imaginary testbed can be modified for convenience and simplicity. For example, instead of chaining numerical models for hundreds of thousands of nodes and links in a given network with hundreds of thousands of end-users, a simplified and smaller version of the models that use dozens of nodes, links, and end-users can be tested and verified before scaling up. Imaginary testbeds enable simplified analysis and verification. Imaginary testbeds are helpful as well when security is of the utmost importance, such as identifying the location of key infrastructure, as well as when the sensitivity of the results is important, such as simulating terrorist attacks so as not to scare people living in an actual community. Thus, security and sensitivity concerns could arise from the nature of the data or analytical results, as well as from the potential trauma and alarm that could be garnered from the publication of the simulation results.

Nonetheless, testbeds are not limited to imaginary communities but can model a real world community too. How well the testbed models the real community (e.g., the level of detail captured in the testbed) varies depending on the availability and type of data, as well as the analytical needs. For the latter, a testbed may need to model a community on a building-level basis or on a larger scale such as a census block basis. Some testbeds model real communities with high-resolution details. Take the Harris County testbed for example, which was constructed using data from Harris County, Texas. The Harris County testbed modeled power, gas, healthcare, and transportation networks along with the regional topology to simulate and measure the risk of flood hazard scenarios (Dong et al. 2020b). This was done to mirror the real conditions of the county in the testbed as best as possible. Upkeep of data can be a pressing concern and is needed for testbeds modeling real communities. On the other hand, some testbeds, such as pseudo-Norman, roughly model an existing community using only a few of its attributes. The pseudo-Norman testbed is a coarse replica of the city of Norman, Oklahoma. Since the testbed includes only some aspects of Norman and is not an exact representation of Norman, the originating authors named it *pseudo*-Norman (Masoomi and van de Lindt 2017).

As evident here, testbeds come in a variety of shapes and sizes. To understand what it means to be a testbed, we designed and virtually administered an expert survey and coupled these findings with our synthesis from a systemic literature review.

Expert Survey

An expert survey was developed in Qualtrics, a powerful online survey tool, to obtain a consensus definition for the term testbed; the survey data and report are published on DesignSafe-CI (Sutley et al. 2021a; Enderami and Sutley 2021). A link to the survey was emailed to 267 experts, where 90 responses were received for a response rate of 34%. This human subject research was approved by the University of Kansas Institutional Review Board (STUDY00147164). Experts were identified in one of two ways. First, 153 experts were identified as an author on one or more of the testbed publications reviewed in the systematic literature review (inclusion/exclusion criteria for the literature review are described later). Although there are more authors than 153 on the papers included in the literature review, the email addresses could be obtained online for only 153. Second, based on our team's experience and professional network, we were aware of other ongoing projects that we are developing or using testbeds; from that, we came up with a list of 114 additional experts. This totaled 267 experts; however, in the recruitment email, respondents were asked to share the link with any collaborators they considered as testbed experts. No personally identifiable information was collected from respondents, so we do not know how many people the survey was shared with outside of the 267 experts we directly emailed. We suspect this number is quite low and that the overall response rate is very near the calculated response rate of 34%.

The survey consisted of a series of questions to categorize respondents, including position, disciplinary expertise, and whether the respondent had used a testbed before or not. If the respondent had used a testbed before, they were asked which testbed(s) they had experience with, which hazards and types of systems they had examined in their use of a testbed, where they obtained data or architecture for the testbed(s), and if any validation had been performed by them or otherwise on the testbed(s). The remainder of the survey consisted of a series of questions intended to define what a testbed is with explicit differentiation from a case study. Results from selected questions are presented and discussed herein.

Fig. 1 provides responses from the first two survey questions on the primary discipline and position of the 90 respondents. As shown in Fig. 1(a), nearly two-thirds of respondents' primary discipline is the same as this paper's authors, civil engineering. However, the

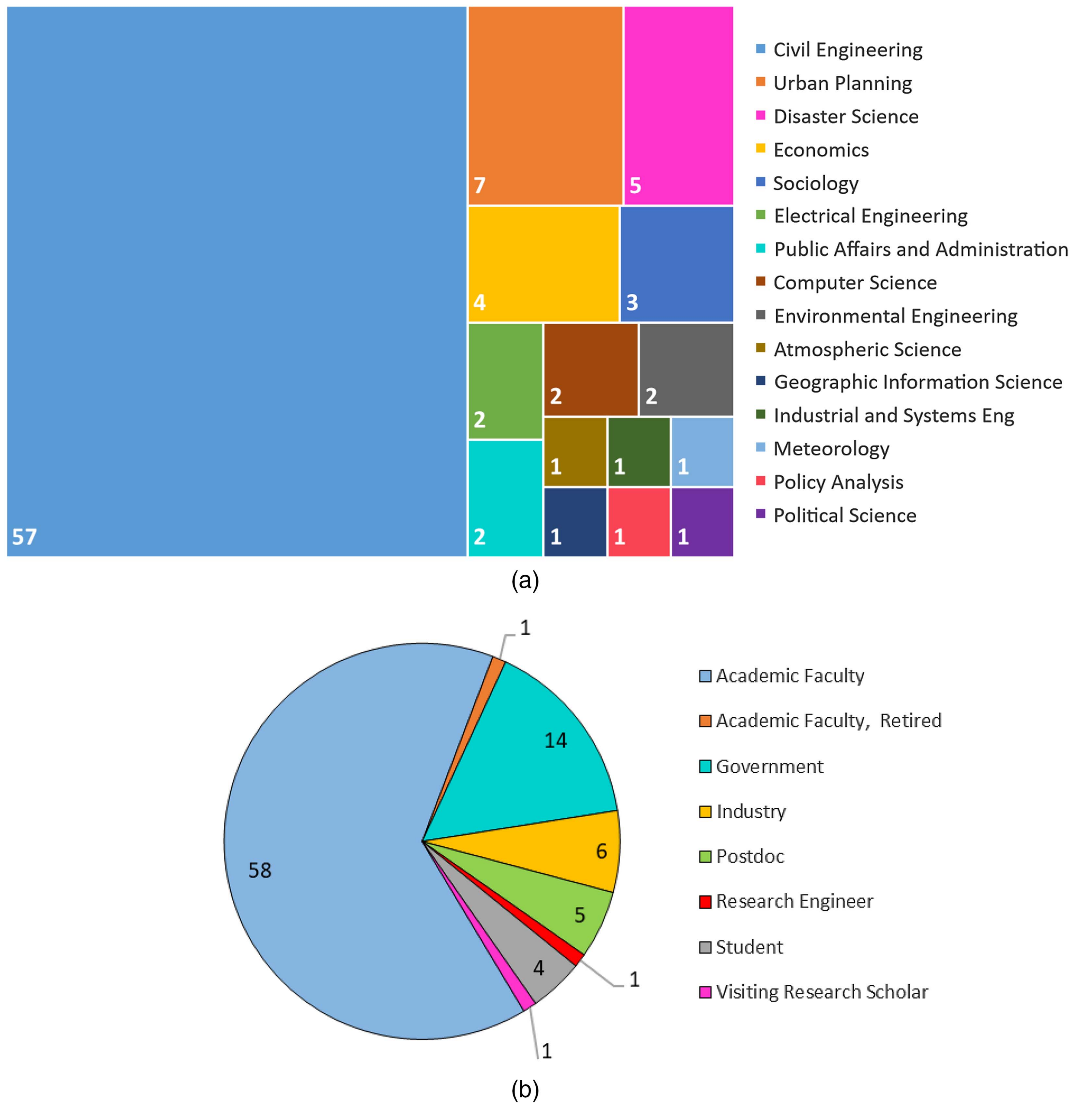

Fig. 1. Primary (a) discipline; and (b) position of survey respondents (n = 90).

remaining one-third span diverse disciplines in engineering, social and physical sciences. Similarly, as shown in Fig. 1(b), nearly 75% of respondents identified their position as academic-based, whether faculty, retired faculty, postdoc, or student. However, 15% of respondents work in government positions, and 7% work in industry. Of the 90 completed surveys, 58 respondents indicated that they personally had used a testbed before. Although we are not sure the exact reasons behind the 32 identified experts who indicated they had not personally used a testbed, we are anecdotally aware of many cases where teams of people work together on a project and some team members work directly with computational algorithms and testbeds while other team members provide feedback, discussion, idea generation, and the like. Thus, the latter category of team members is very familiar with testbeds even if they personally had not used one before.

Defining a Testbed

The term testbed has been used across many disciplines to test scientific theories, computational tools, and new technologies. Meriam-Webster (https://www.merriam-webster.com/) defines the word "testbed" as "any device, facility, or means for testing something in development." This definition does not fully align with how testbeds have been applied in the literature, and it is insufficient in capturing the specific needs for community resilience analysis. We believe a testbed is more than a device or facility; so, we included two open-ended questions in the survey to facilitate consensus on the definition of a testbed. The questions provided our proposed definitions of a testbed and a case study and requested the respondent for any comments to refine the definitions. Based on the 96 comments received from these two questions, along with comments recorded from other open-ended questions, we made the required revisions to form the following consensus definition for a testbed:

A testbed is an *environment* with enough supporting architecture and metadata to be representative of one or more systems such that the testbed can be used to (1) design experiments, (2) examine model or system integration, and (3) test theories.

The concept of virtual community resilience overlaps with some existing commercial catastrophe modeling software, publicly available tools for hazard mitigation and preparedness planning (e.g., HAZUS), or other modern high-tech simulation tools such as a digital twin. But these tools do not fit into the proposed definition of the testbeds, although they might be effective tools in community resilience research. For example, existing risk assessment tools do not provide the required architecture for designing experiments, examining models that include social and economic aspects of a

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community, and integrating them into the other components. For example, a digital twin of a community is a virtual environment that represents the physical aspects of a community and does not simulate the other dimensions of a community. In the survey, a complementary open-ended question was also asked, "*What, if any, minimum requirements are necessary for something to be considered a testbed?*". Sixty-six responses were received. Qualitative analysis revealed three categories of comments: (1) applicability of the testbed to be applied to research questions; (2) requirements of what must be modeled (e.g., systems, hazards); and (3) the accessibility and documentation of the testbed for the research community. The first category was coded into two themes. These two themes were that the testbed must (1) represent reality, and (2) be a real community. The second category was coded into three themes: the testbed must include models of (1) multiple hazard options (e.g., type, level); (2) multiple systems; and (3) must have humans. The third category was coded into eight themes, including that the testbed must: (1) be developed and useable from a multidisciplinary team or perspective; (2) have broad applicability for examining different community resilience algorithms to answer a broad range of research questions relevant for the community at hand; (3) have a defined purpose; (4) be accessible to other users outside the original developers; (5) well-documented; (6) replicable or reliable; (7) scalable; and (8) open-source or modifiable. Finally, two other themes were not categorized: (1) that there are no minimum requirements for something to be defined as a testbed; and (2) other, which included comments not captured by the other 14 themes. The number of responses classified into each of the 15 themes is depicted in Fig. 2. The most common response was that at a minimum, a testbed should represent reality ($n = 21$). Three of the 21 comments distinguished that the testbed must indeed be real, as opposed to only a representation of reality. The second most common response was that a testbed should be broadly applicable ($n = 20$); whereas 9 responses indicated a testbed must have a defined, specific purpose.

Distinguishing a Testbed from a Case Study

Although distinct concepts and not synonymous terms, the words *testbed* and *case study* are often used interchangeably (particularly in community resilience studies), which has the potential to be misleading. Both case studies and testbeds can be utilized at the community level, but testbed is not a term frequently used in conjunction with a study of a specific past event or single system. Here, we define a case study as research performed to glean new insight from the analysis of a specific situation or demonstrate analysis results. This definition received consensus from the expert survey. A distinguishing feature between a testbed and a case study is that in a testbed, the researchers have some level of control in the design of a testbed and can project a range of scenarios or events, whereas this is not true with a case study. To better illustrate ways to distinguish a testbed from a case study, two examples are provided from the literature.

Galveston, TX, is a community with a long history of hurricanes and has been studied by many hazards and disasters researchers. Hamideh and Rongerude (2018) studied the impacts of community members' social vulnerability in their participation in disaster recovery decisions using Galveston's public housing after Hurricane Ike as a case study. In another study, Fereshtehnejad et al. (2021) developed a Galveston testbed for studying the cumulative impact of hurricane-induced damages to civil infrastructure and evacuation decisions of the population. The former was a specific study documenting what happened to a specific group of people following Hurricane Ike. The latter consisted of multiple models chained together capable of simulating and assessing a range of hazard scenarios and subsequent impacts for Galveston.

Similarly, after Lumberton, NC, was flooded following 2016 Hurricane Matthew, a team of researchers began a longitudinal field study to collect cross-disciplinary data on impact and recovery (van de Lindt et al. 2018). Many analyses use this data taking the form of case studies [see (Aghababaei et al. 2019)]. However, the

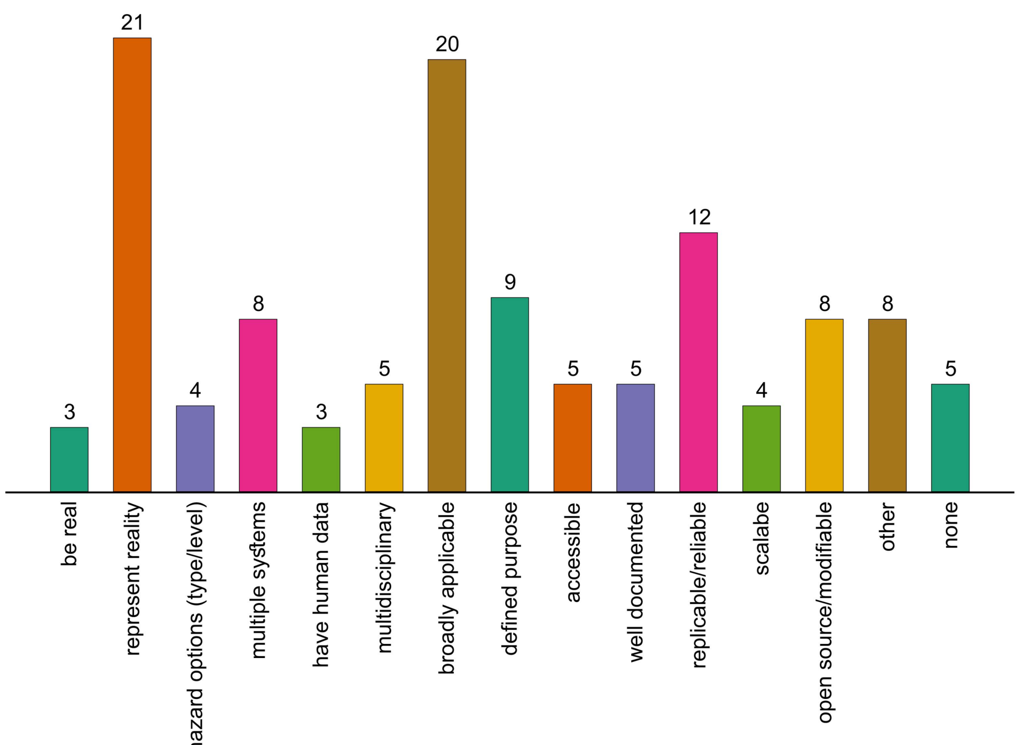

Fig. 2. Expert-identified minimum requirements for a testbed.

larger research team is also building a virtual testbed of Lumberton for model validation purposes. Nofal and van de Lindt used the Lumberton testbed as both a case study to look at the specific one-time scenario of the 2016 flooding (Nofal and van de Lindt 2020c) and a testbed to evaluate the vulnerability to flooding and the effectiveness of different mitigation strategies (Nofal and van de Lindt 2020a, b). This has become common to develop testbeds of communities that are rich in case studies.

The expert survey asked respondents one open-ended question to help distinguish a case study from a testbed. Sixty-nine responses were received to the question, "*How do you describe the differences between a testbed and a case study?*" Responses pointed to differences in the scale of the analysis, being able to simulate predictions and interventions with testbeds and the broader use of testbeds. Whereas case studies must be real, apply a predesigned methodology by the researcher(s), and be limited to a particular study objective.

Five prompts followed that requested respondents to categorize each prompt as describing a testbed, a case study, both, or neither. The prompts were based on statements identified during the literature review describing testbeds or case studies, as well as through informal conversations with colleagues about testbeds and case studies. The five prompts read as follows:

1. A zipped folder containing geospatial data of building footprints, road networks, hazard probability, and population demographics all for a particular community.
2. A zipped folder containing geospatial data of building footprints, road networks, hazard probability, population demographics all for a particular community, along with the algorithm script for simulating hazard occurrence, physical damage, and restoration processes.
3. The script file and results from a regression analysis performed on damage and disruption data collected in the field using survey methods after a specific hurricane.
4. A paper presenting a "proof of concept" test for risk assessment involving 1. Assessment of seismic hazard and ground motions for City-A; 2. Definition of the inventory for buildings, bridges, and utility lines in City-A; 3. Development of vulnerability curves for buildings and bridges in the area; 4. Evaluation of economic impact on property owners and businesses, disruption of social services, and factors influencing local decision making; 5. Recommendation of mitigation measures for improved seismic safety; 6. Creation of decision support tools for comparing solutions for seismic mitigation.
5. On-the-ground investigation into the failure sequence of a particular building damaged during a tornado.

Fig. 3 provides the classifications from these five prompts, where each prompt was classified in multiple categories by different respondents. Prompt *ii* received 70 responses, whereas the other four prompts all received 71 responses. As evident in Fig. 3, there was fair variability across the five prompts, where prompt *v* got the most consistent responses (86% categorizing as a case study). Of note, 18 of the 70 and 19 of the 71 were from respondents who indicated they had not used a testbed before, and there was still proportional variability in classification from respondents who had used a testbed before. An open-ended question followed the five prompts requesting respondents to share any comments about the classification; 19 responses were recorded. Comments were mostly in line with our team's intention in the ill-defined prompts in that prompt *i* is considered data and would be classified as other, prompt *ii* is essentially a testbed, prompt *iii* describes the components of an analysis that is likely enabled because of a case study and would be classified as other, prompt *iv* is a paper presenting an analysis and would be classified as other, and prompt *v* is a field-based case study. As shown in Fig. 3, the highest agreement between our team

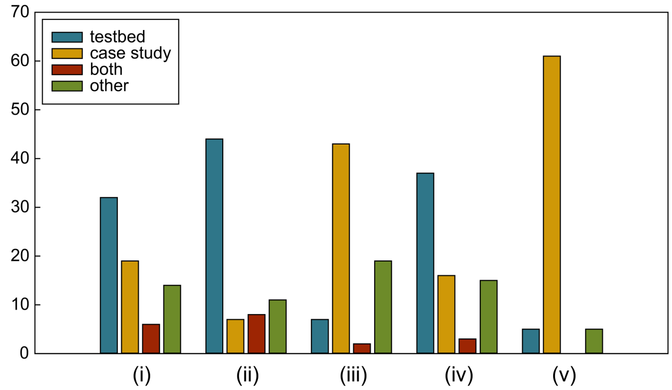

Fig. 3. Classifying five descriptions as a testbed, case study, both, or other.

and the respondents were with classifying prompt *ii* as a testbed (63% of respondents), and prompt *v* as a case study (86% of respondents). Prompt *ii* is a good example of a real testbed (since it is for a particular community) that provides metadata (i.e.; geospatial data of building footprints, road networks, population demographics, hazard probability) and supporting architecture (i.e. algorithm script for simulating hazard occurrence, physical damage, and restoration processes). The testbed can be used to design and examine various community resilience models to answer a broad range of research questions such as assessing physical vulnerability, postdisaster accessibility, and social service disruptions.

Furthermore, despite many respondents also identifying prompt *iv* as a testbed, the open-ended responses following these prompts indicated that most respondents overlooked the fact that testbeds are inherently virtual *environments*, while prompt *iv* is limited to just a *paper*. A soft copy (e-version) of the script defined in prompt *iv* would be essentially a testbed, a virtual environment with enough supporting architecture and metadata that it can be applied to examine different community resilience algorithms to answer a broad range of research questions regarding City-A. This means despite the agreement between researchers on the definition of the testbed and case study, there are still some discrepancies in how these terms are distinguished and used in practice.

Existing Virtual Testbeds

This section presents findings from a systematic literature review on testbeds used for community resilience analysis. Papers were identified using specific keywords, including "testbed," "test bed," "case study," "test case," "virtual city," and "Benchmark City." Three inclusion/exclusion criteria were used for categorizing identified papers in the literature review. First, the paper had to use the testbed for studying the impact of hazards on the community. Even though some of the testbeds included in our review were initiated for purposes other than community resilience research, they are included here if they otherwise fit the consensus definition of a testbed and have been extended later by incorporating a hazard module or social and economic systems into the testbed. As an example, Mazumder et al. (2020) added a hazard module to the Anytown testbed (Walski et al. 1987), which had not been used previously for community resilience analysis. Of note, the application of virtual testbeds for community-level analyses has been popularized among researchers from different disciplines such as environmental science, meteorology, engineering, sociology, urban

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planning, and disaster science. The NOAA Hydrometeorology Testbed (HMT) was developed by the Office of Oceanic and Atmospheric Research and the National Weather Service to improve and advance extreme precipitation and hydrologic predictions (Schneider et al. 2010). Although HMT represents a novel and important testbed, associated publications were excluded from this review since HMT does not meet the first inclusion criteria for a community resilience testbed.

Second, the paper had to develop or use a testbed, as opposed to a case study; the criteria for this are fully described in the expert survey sections of this paper. As a rule of thumb, in a case study, the researcher examines the impacts of the specific event(s) on the intended community. Whereas, the goal of developing a testbed is to provide an environment with the potential of being used for evaluating different community resilience algorithms and models under different events. Third, the paper had to otherwise align with the proposed definition of a testbed. Papers utilizing the ASCE Structural Control Benchmarks (Dyke et al. 2003), Virtual Supervisory Control and Data Acquisition (Dayal et al. 2015), and Southern California Planning Model (RICHARDSON and DAVIS 1998) testbeds were excluded from this review given that they do not have enough components to be used for the specified purposes in the testbed definition.

Considering the aforementioned criteria, 22 testbeds including 12 imaginary and 10 real communities are identified and incorporated into this review. Table 1 provides a comprehensive list of the 22 testbeds reviewed, including a short description of their development timeline and identified publication inventory. Although the identified testbeds differ in terms of development level, all of them meet the designated inclusion/exclusion criteria. The testbeds in Table 1 are introduced through their hazard module, building and infrastructure inventory, and socioeconomic systems, if any. Also, Table 1 provides a summary of each testbed's V&V process (if any), introduces the testbed's data resources (if known), and explains how to access the testbed's data (if available). The sections that follow describe commonalities, gaps, and other observations on hazard modules and community modules across testbeds with comparisons to the expert survey responses where possible.

Inclusion of Hazard Module in Community Resilience Testbeds

The hazard module in the majority of the reviewed testbeds comprises natural hazard scenarios such as earthquake, hurricane-induced flood and wind, tornado, and tsunami. However, manmade hazards including contamination, cyber-physical attack, and urban fire are modeled in Micropolis, Mesopolis, and C-Town testbeds. CLARC is the only testbed with a hazard module including both natural and manmade hazard models together. Little et al. (2021) employed the CLARC testbed to investigate the effects of a global pandemic on a community recovery time following a hurricane. A few of the reviewed testbeds such as Harris County, CLARC, Galveston, Centerville, Seaside, and Atlantic County employ a hazard module with multihazard models and provide the opportunity to assess the cumulative impacts of the cascading hazards. The hurricane models in CLARC, Galveston, and Atlantic County testbeds enable researchers to study the consequences of both flood- and wind-induced disruptions together. The hazard module of the Seaside testbed consists of a tsunamigenic earthquake model that considers both earthquake shakings and tsunami inundation (Fereshtehnejad et al. 2021; Little et al. 2020; McKenna et al. 2021; Park et al. 2019). Other than Galveston, Mesopolis, and Seaside testbeds that benefit from probabilistic approaches to simulate future events and predict their impacts; the other reviewed testbeds employ scenario events (either one single event or a suite of synthetic scenarios that happened in the past) in their hazard modules (Fereshtehnejad et al. 2021; Park et al. 2019; Torres et al. 2009). Fig. 4 compares the number of testbeds with a particular hazard module across different hazard types with the number of identified publications applying those hazard modules and the number of survey respondents who indicated they personally had examined such hazard type in a testbed. In Fig. 4, the number of testbeds with earthquake hazard models is significantly higher than that of other hazard types. On the other hand, tsunami hazard is rarely included in testbeds. Of note, the Seaside testbed that models tsunami hazard has been used in nine different studies (González et al. 2009; Kameshwar et al. 2019; Mostafizi et al. 2017; Park et al. 2019; Park and Cox 2016; Park et al. 2017; Priest et al. 2015; Wang et al. 2016; Wiebe and Cox 2014). Anytown, C-Town, and unnamed water network were initiated without a hazard module; however, Anytown, unnamed water network, and C-Town were supplemented later by appending a hazard module (Mazumder et al. 2022, 2020; Nikolopoulos et al. 2020; Taormina et al. 2016). As evident in Fig. 4, there is a direct relationship between the number of existing testbeds and identified publications across every hazard type except hurricane-induced floods with the number of respondents who indicated they had examined that hazard type to a testbed. The greater number of respondents who have personal experience of applying flood hazards to a testbed compared to the other types of hazards may result in a slight bias in the survey results, however, there is still fair variability in the experience of the respondents.

Inclusion of Community Module in Community Resilience Testbeds

The community module of a testbed is a geospatial model of one or preferably more interconnected physical, social and economic systems; however, including either of the three systems is adequate to initiate the community module of a testbed. As identified in the literature review, most papers to date have focused initially on modeling physical systems, whereas in a community resilience study, it is important to also capture the community's social and economic systems and cascading effects of their failure. Also, in the existing testbeds, researchers have resorted to simplifying their physical system models to reduced order physical models (such as Turin Virtual City) or fragility-based statistical models. However, along with advances in computational science and technologies, classical finite element models and data-driven machine learning models are likely to be applied in future testbeds.

Physical System: The physical system of the existing testbeds includes the community's building inventory and/or infrastructures-asset inventory such as water, electric power, gas, transportation, communication, wastewater, and drainage networks. Of note, all of these infrastructures are not modeled for every existing testbed; only 6 out of the 22 reviewed testbeds (namely, Shelby County, Benchmark City, CLARC, Gotham City, Centerville, and Seaside) include more than three infrastructure types besides their building inventory. The physical system in four testbeds, including Anytown, C-Town, the unnamed water network, and Mesopolis consists of water networks only (Alvisi and Franchini 2011; Islam et al. 2011; Johnston and Brumbelow 2008; Walski et al. 1987). Turin Virtual City, Atlantic County, and Lumberton solely included the community's building inventory to create their physical system (Lindt et al. 2020; McKenna et al. 2021; Noori et al. 2017). The physical systems in the UW Power Systems Test Case Archive only consider electrical power networks (Didier et al. 2015). Of the testbeds that do incorporate more than one type of infrastructure, many remain uncoupled and are presented in independent analyses in separate

Table 1. Summary of existing virtual testbeds included in the review

Testbed	Description	Identified publications
CLARC	The Customizable Artificial Community (CLARC) is a virtual imaginary testbed based on the scaled data inventory of New Hanover County, North Carolina. The CLARC testbed was initiated by Loggins and Wallace (2015) to demonstrate the benefits of modeling interdependencies among a community's infrastructure assets when estimating disruptions arising from hurricanes. Later, Little et al. (2020) and Loggins et al. (2019) advanced the testbed to study the interdependencies between a community's civil and civic infrastructure and to validate their novel proposed model (CRISIS) for community recovery following a hurricane. The CLARC testbed represents a coastal community with a population of approximately 500,000 located in 77 census blocks. The testbed's community module consists of residential building inventory (at the census block level), power, water, wastewater, transportation, communication networks, and a few civic infrastructures (such as public safety, healthcare, fuel, and banking) and demographic data. The CLARC dataset is developed as a GIS database that is housed in Microsoft Access and is available via https://doi.org/10.17603/DS2FX2D (Little et al. 2020). During the COVID-19 pandemic, Little et al. (2021) employed the CLARC testbed and CRISIS model to investigate the effects of a global pandemic on community recovery time following a hurricane.	Loggins and Wallace (2015), Loggins et al. (2019), Little et al. (2020, 2021)
Centerville	The Centerville Virtual Community is an imaginary testbed initiated by Ellingwood et al. (2016a) to be used for developing community-level resilience assessment approaches that consider the cumulative impacts of natural hazards to the community's physical, social, and economic systems. The testbed represents a middle-class Midwestern State city in the US with a population of about 50,000 which is situated approximately 50 miles from the New Madrid Seismic Zone and close to tornado alley (Ellingwood et al. 2016a). So far, the testbed has been mostly applied to study the consequences of earthquakes and tornados. (Cutler et al. 2016; Daniel et al. 2022; Lin and Wang 2016; Lin and Wang 2017; Sutley and Hamideh 2020; van de Lindt et al. 2016; Zhang and Nicholson 2016). However, the testbed has the potential to be used in other hazard scenarios. For instance, Zou and Chen (2020) applied a hurricane hazard scenario on the Centerville testbed. The infrastructures considered in the testbed include the buildings (13 building occupancy types in 16 building archetypes), water, electrical power, and transportation networks (Ellingwood et al. 2016a). The testbed's social system consists of hypothetical demographics (such as the number of households, households mean income, owner or renter status, population number, diversity, sex, and age range), population dislocation (Ellingwood et al. 2016a), social vulnerability level assignment to households and housing recovery models (Sutley and Hamideh 2020). Also, a dynamic spatial computable general equilibrium (CGE) model is incorporated into the community module to establish the testbed's economic system. (Cutler et al. 2016). The testbed datasets have been fully incorporated into IN-CORE (interdependent networked community resilience modeling environment (Gardoni et al. 2018)) and its datasets are accessible for the researchers.	Ellingwood et al. (2016a, b), Lin and Wang (2016), van de Lindt et al. (2016), Cutler et al. (2016), Zhang and Nicholson (2016), Guidotti et al. (2016), Lin and Wang (2017), Sutley and Hamideh (2020), Zou and Chen (2020), Daniel et al. (2022)
Benchmark City (China)	A GIS-based virtual imaginary testbed named Benchmark City was created by Shang et al. (2020) based on a common midsize city located in the southeastern coastal region of China. The testbed is used for evaluating existing resilience assessment frameworks for Chinese cities. The required information such as demographics, site condition, land-use class, potential hazard (i.e.; earthquake hazard), infrastructure inventory (including power, transportation, water, drainage, and natural gas distribution networks), and location of hospitals, emergency shelters, and schools are hypothetically considered by Shang et al. (2020). Jichao et al. (2021) applied the Benchmark City testbed to assess the seismic functionality of the city's water distribution network.	Shang et al. (2020), Jichao et al. (2021)

Table 1. (*Continued.*)

Testbed	Description	Identified publications
Shelby County	Shinozuka et al. (1998) initiated the Shelby County, Tennessee testbed in 1998 for investigating the effects of seismic damages to the electrical power system on the local community's economy. Since then, the testbed's hazard module has been developed slightly by adding more earthquake scenarios, whereas its community module has been developed significantly by multiple research groups for different research purposes (Adachi and Ellingwood 2009; Chang and Shinozuka 2004; Dueñas-Osorio et al. 2007; Hwang et al. 2000; Johansen and Tien 2018; Lin and El-Tawil 2020; Roohi et al. 2021; Wu and Dueñas-Osorio 2013; Zhang et al. 2018). So far, the community module's physical system includes data on the community's building inventory (Roohi et al. 2021; Zhang et al. 2018), water (Chang and Shinozuka 2004), power (Shinozuka et al. 1998), gas (Adachi and Ellingwood 2009; Dueñas-Osorio et al. 2007; Johansen and Tien 2018; Wu and Dueñas-Osorio 2013), and transportation networks (Hwang et al. 2000). Shinozuka et al. (1998) initially applied a classic input-output impact model to build the community module's economic system for regional impact analysis; afterward, Roohi et al. (2021) incorporated a CGE model into the testbed's economic system. A population dislocation model is also employed by Roohi et al. (2021) to establish the testbed's social system.	Shinozuka et al. (1998), Hwang et al. (2000), Chang and Shinozuka (2004), Adachi and Ellingwood (2009), Dueñas-Osorio et al. (2007), Wu and Dueñas-Osorio (2013), Johansen and Tien (2018), Zhang et al. (2018), Lin and El-Tawil (2020), Roohi et al. (2021)
Seaside	Seaside, OR is a small low-lying coastal city with a population of approximately 6,000 residents in the US Pacific Northwest. The city is susceptible to tsunamigenic earthquakes originating from the Cascadia Subduction Zone (CSZ) (González et al. 2009; Park and Cox 2016). The testbed hazard module includes multi-hazards cascading seismic and tsunami scenarios. The testbed's community module has been developed in multiple phases; as yet, building inventory (Park et al. 2017; Wiebe and Cox 2014), water (Rosenheim et al. 2021) and power (Kameshwar et al. 2019) networks, roads (Wang et al. 2016), and bridges (Priest et al. 2015) are the physical systems that have been incorporated into the testbed's community module. A multihazard damage analysis model that combines the earthquake- and tsunami-induced damages is also appended to the testbed's community model (Park et al. 2019). A set of demographic data such as population density (Wang et al. 2016) and a community evacuation model (Mostafizi et al. 2017) build the testbed's social system. The testbed datasets have been incorporated into IN-CORE (Gardoni et al. 2018) and its datasets are accessible to the researchers.	González et al. (2009), Wiebe and Cox (2014), Priest et al. (2015), Wang et al. (2016), Park and Cox (2016), Mostafizi et al. (2017), Park et al. (2017), Rosenheim et al. (2021), Kameshwar et al. (2019), Park et al. (2019)
Galveston	The city of Galveston is a barrier island located off the coast of Texas in the Gulf of Mexico. The main motivation for creating the Galveston testbed was to use it for studying community resilience metrics of coastal communities under hurricane-induced hazards such as surge, wave, inundation, and wind. The Center for Risk-Based Community Resilience Planning released Galveston Testbed as a library in the IN-CORE (Gardoni et al. 2018). So far, the testbed's hazard module encompasses wind, riverine and storm-surge flooding models (Czajkowski et al. 2013; He and Cha 2018). A residential building portfolio (Czajkowski et al. 2013), an electric power network (He and Cha 2018), and transportation-related datasets (Gardoni et al. 2018) create the community module's physical systems. To estimate hurricane-induced damages, parametrized fragility models for buildings, coastal bridges, and coastal roadways are incorporated into the community module (Fereshtehnejad et al. 2021). The social system of the community module includes a population dislocation and a housing unit allocation model that enables using US Census household-level data for assessing the social impacts of the hurricane hazards (Gardoni et al. 2018).	Islam et al. (2010), Czajkowski et al. (2013), He and Cha (2018), Hamideh and Rongerude (2018), Fereshtehnejad et al. (2021)

Table 1. (*Continued.*)

Testbed	Description	Identified publications
Gotham City	Gotham City is a virtual imaginary testbed created by Mahmoud and Chulahwat (2018) to be used for demonstrating and verifying community resilience models. The city is divided into four regions which are connected through bridges only. The testbed's community module consists of hypothetical social, economic, and physical systems. The physical system encompasses data on water, power, communication, transportation infrastructures, as well as residential and health building inventories for each region. Mahmoud and Chulahwat (2018) used the hypothetical attribute of social and economic systems to compute the social vulnerability index and infrastructure stability matrix for each region. The testbed's hazard module is capable of accommodating various types of hazards that cause physical disruptions, economic downtimes, and even social disorders (Mahmoud and Chulahwat 2019).	Mahmoud and Chulahwat (2018, 2019)
Harris County	Harris County, TX, is a hurricane-prone county located near the Gulf Coast in the United States. The testbed has been advanced in multiple phases for different research purposes. So far, the community module's physical system consists of models for the power and gas transmission infrastructure and their cascading failure effects (Ouyang and Dueñas-Osorio 2012, 2014, 2011; Ouyang et al. 2012; Ouyang and Wang 2015) as well as transportation networks (Dong et al. 2020a, b; Fan et al. 2020). The traffic data of the transportation network are collected from INRIX (https://inrix.com), a private company providing location-based data and analytics, and so are not publicly available. The testbed's hazard module encompasses a series of pre-generated hurricane scenarios that can cause floods and inundation (Fan et al. 2020; Ouyang and Dueñas-Osorio 2012, 2014, 2011; Ouyang et al. 2012; Ouyang and Wang 2015).	Ouyang and Dueñas-Osorio (2011, 2012), Ouyang et al. (2012), Ouyang and Dueñas-Osorio (2014), Ouyang and Wang (2015), Dong et al. (2020a, b), Fan et al. (2020)
Gilroy	The Gilroy testbed is modeled after the real city of Gilroy, CA; a moderate-size town located approximately 6 miles from the San Andreas Fault. The testbed was initially created by Nozhati et al. (2018a) to study the relationship between specific community resilience metrics (e.g.; food security, post-earthquake recovery) and interdependent critical infrastructure (such as energy, transportation, and water systems) following a seismic event. A scenario earthquake with a magnitude of 6.9 (similar to the Loma Prieta Earthquake 1989) builds the testbed's hazard module (Nozhati et al. 2018a). The community module's physical system comprises data on electrical power networks, water systems, highway bridges, and food retailers. The community module's social system consists of a set of demographic data (such as population density) from the 2010 census database (Nozhati et al. 2018a, b, c, 2019a, b, c, 2020a, b; Sarkale et al. 2018).	Nozhati et al. (2018a, b, c), Sarkale et al. (2018), Nozhati et al. (2019a, b, c, 2020a, b)
pseudo-Norman	The pseudo-Norman testbed is a simplified coarse model after the real city Norman, OK. The testbed was initially created by Masoomi and van de Lindt (2017) to investigate the community-level risk and recovery modeling after a tornado. The testbed takes only a few attributes of the Norman community into account; therefore, it is called *pseudo-Norman*. The testbed's community module includes data on households and businesses, residential and school buildings, and water and electric power networks. A few aspects of demographics such as the population, the number of students, and employees are also appended to the community module (Masoomi and van de Lindt 2017). The testbed datasets have not been published separately, but, the primary parameter that has been used for developing community and hazard modules can be found in the published works on the testbed (Masoomi et al. 2018; Masoomi and van de Lindt 2017).	Masoomi and van de Lindt (2017), Masoomi et al. (2018)

Table 1. (*Continued.*)

Testbed	Description	Identified publications
Joplin	The Joplin testbed represents the city of Joplin located in the southwest of the Missouri State. The testbed was created following the EF5 Joplin tornado in 2011 to assess the disruptions due to hurricane-induced damages to interdependent infrastructures (particularly buildings and power networks) and the socioeconomic impacts of such disruptions on community recovery (Attary et al. 2019). However, the testbed has been further used to verify and validate building inventory damage models and recovery trajectories (Aghababaei et al. 2020; Pilkington et al. 2021; Pilkington and Mahmoud 2020). The building inventory and power network dataset are the only two components of the testbed's physical system (Attary et al. 2019; Pilkington et al. 2021). The testbed's economic system includes a model that can estimate the economic impacts of scenario tornado-induced disruptions. Also, a population dislocation model at the household level builds the community module's social system (van de Lindt et al. 2019). The testbed's accuracy and validity of social and economic models were verified using results from several case studies on Joplin after the 2011 tornado (Kuligowski et al. 2014). The testbed has been incorporated into IN-CORE (Gardoni et al. 2018) and its datasets are accessible to the researchers. Simulating the tornado event in IN-CORE (Gardoni et al. 2018) allows the researchers to model different tornado scenarios by generating random tornado paths across the community to get a full risk profile (Attary et al. 2019; Pilkington et al. 2020; van de Lindt et al. 2019).	Attary et al. (2019), van de Lindt et al. (2019), Pilkington et al. (2021, 2020), Aghababaei et al. (2020), Pilkington and Mahmoud (2020)
ASCE First Generation Testbed	ASCE First Generation Testbed is an imaginary testbed that has been initiated based on the ASCE Sub-Committee on Disaster Resilience of Structures and Infrastructures proposal. Cimellaro et al. (2014) applied the testbed to compare the pros and cons of different resilience-based design strategies available in the literature. The testbed consists of two critical structures (including a Town Hall and Hospital), a University Campus, and the water distribution network of a small town.	Cimellaro et al. (2014)
Lumberton	Lumberton is a small city in North Carolina, hugely impacted by the Lumber River flooding in 2016 after Hurricane Matthew. After the flooding, comprehensive longitudinal field studies and interdisciplinary technical investigations have collected cross-disciplinary data on impact and recovery (van de Lindt et al. 2020, 2018). The Lumberton testbed was created to investigate the building- and community-level flood vulnerability, and V&V of different community resilience models (Nofal and van de Lindt 2020d). The testbed's hazard module consists of a flood scenario based on a flooding event after Hurricane Matthew in 2016. So far, a building inventory including 15 building archetypes and building damage analysis models using flood fragility functions are incorporated into the testbed's community module (Nofal and van de Lindt 2020a, b, 2021a, b; Nofal et al. 2020, 2021e, f). Also, to assess the social impacts of the flood hazard, a housing unit allocation and a population dislocation model comparable to the Galveston testbed's social models (Gardoni et al. 2018) are appended to the testbed's community module (Rosenheim et al. 2021). The testbed has been incorporated into IN-CORE (Gardoni et al. 2018) and its datasets are accessible to the researchers. Of note, multiple researchers are still working on case studies of business interruption and recovery models that can be used for establishing the testbed's economic system later (Aghababaei et al. 2021; Watson et al. 2020).	van de Lindt et al. (2018), Lindt et al. (2020), Nofal and van de Lindt (2020a, b, d), Nofal et al. (2020), Nofal and van de Lindt (2021a, b), Nofal et al. (2021e, f), Rosenheim et al. (2021), Aghababaei et al. (2021), Watson et al. (2020), Sutley et al. (2021b), Helgeson et al. (2021)

Table 1. (*Continued.*)

Testbed	Description	Identified publications
Atlantic County	Atlantic County, NJ is a county with three adjacent barrier islands that lie along the Atlantic Coastal Plain on the east coast of the United States. The county is prone to hurricane-induced hazards, such as strong wind, riverine flooding, and storm surge on the ocean-facing coastline (NJOEM 2019). The SimCenter, in collaboration with a team of researchers from different universities, developed the Atlantic County testbed to be used for introducing the implementation of SimCenter's Hurricane Regional Loss Modeling Workflow (McKenna et al. 2021). However, the testbed can be used for other regional studies. Wind and storm surge models are incorporated into the testbed's hazard module (McKenna et al. 2021). The testbed's building inventory encompasses the required attributes of community buildings at the parcel level (McKenna et al. 2021). The Building Footprint Data obtained from the New Jersey Department of Environmental Protection, Microsoft Footprint Database (Microsoft 2020), New Jersey Tax Assessor Database (NewJerseyOfficeofGIS 2021), and computer vision methods (Wang et al. 2021) were utilized to create the testbed's building inventory. Although such attempts can partially validate the accuracy of the building inventory dataset, the quality of the data has not been guaranteed by the developers. The testbed datasets can be downloaded from https://nheri-simcenter.github.io/R2D-Documentation/common/testbeds/atlantic_city/index.html (McKenna et al. 2021).	McKenna et al. (2021)
San Francisco Bay Area	The San Francisco Bay Area is a region in Northern California with a population of more than 7.7 million and three large cities including San Francisco, Oakland, and San Jose. The Bay Area is located close to the San Andreas and Hayward faults which are capable of magnitude 8.0 and 7.0 earthquakes, respectively (Aagaard et al. 2016). The risk from such earthquakes to the built environment has always been of interest to researchers, practitioners, and policymakers. From our research, Kiremidjian et al. (2007) initiated San Francisco Bay Area testbed to assess the risk of a magnitude 7.0 scenario event on the Hayward fault to the Bay's transportation network. Later, the San Francisco testbed was demonstrated in the guise of an example in SimCenter's regional Workflow for Hazard and Loss Estimation of buildings (Elhaddad et al. 2019). The testbed's hazard module comprises a magnitude 7.0 Hayward earthquake scenario (Rodgers et al. 2019). The testbed's community module encompasses a building inventory of 1.8 M buildings located in the Bay Area (except Alameda County and fSan Francisco Tall Building) (Elhaddad et al. 2019). The accuracy and quality of the inventory were verified by cross-referencing the input datasets. A sample dataset of the San Francisco Testbed is available at DesignSafe-CI Data Depot or by submitting a request to https://simcenter-messageboard.designsafe-ci.org/smf/index.php?board=8.0 (Elhaddad et al. 2019).	Kiremidjian et al. (2007), Elhaddad et al. (2019)
Micropolis	Micropolis is a small, virtual, imaginary city of approximately 5,000 residents initiated as a testbed for the development of infrastructure models, particularly water distribution systems. The testbed's community module has been supplemented by adding a power distribution network layout (Bagchi 2009). To provide the required information for replicating the infrastructures of a real typical small city in a historical rural region, a timeline spanning 130 years is created. This hypothetical timeline was used for the design of infrastructure systems, mapping roads and buildings (Brumbelow et al. 2007). The testbed has been applied for manmade hazards such as water supply contamination and urban fire (Bagchi 2009; Torres et al. 2009).	Brumbelow et al. (2007), Bagchi (2009), Torres et al. (2009)

Table 1. (*Continued.*)

Testbed	Description	Identified publications
Turin Virtual City	The Turin Virtual City was created after the city of Turin, Italy, for predicting the physical impacts of a seismic hazard scenario on the building inventory of an urban area (Noori et al. 2017). The testbed's hazard module consists of a seismic hazard scenario recorded during the 2016 Central Italy earthquake. The testbed's community module encompasses a building inventory consisting of 30,122 buildings with different occupancy types and socioeconomic roles.	Noori et al. (2017)
Anytown	The Anytown virtual water distribution network is an imaginary testbed initiated by Walski et al. (1987) for the 'Battle of the Network Models' workshop. The testbed represents a water distribution network of a hypothetical old town in the United States with common characteristics and issues of real water distribution systems. The primary objective of developing Anytown was determining an economically effective design approach for reinforcing the existing system to meet projected demands. Researchers further applied the testbed for the purpose of water system design optimization (Atkinson et al. 2014; Farmani et al. 2005; Herstein and Filion 2011; Prasad and Tanyimboh 2008) and resilience analysis (Mazumder et al. 2020; Salehi et al. 2018).	Walski et al. (1987), Farmani et al. (2005), Prasad and Tanyimboh (2008), Herstein and Filion (2011), Atkinson et al. (2014), Salehi et al. (2018), Mazumder et al. (2020)
Unnamed water network	The *unnamed water network* is a virtual simplified water distribution system that has been constructed to serve as a testbed for research on water distribution systems (Islam et al. 2011, 2014; Shuang et al. 2017, 2014). The testbed has not been named although it has been applied in several studies. The testbed did not have a hazard module until Mazumder et al. (2022) developed a scenario earthquake model to implement a post-earthquake analysis on the testbed.	Islam et al. (2011, 2014), Shuang et al. (2014, 2017), Mazumder et al. (2022)
UW Power Systems Test Case Archive	The UW Power System Test Case Archive is a website that provides required datasets for modeling common 1960s power systems in the Midwestern United States. The website (https://labs.ece.uw.edu/pstca/) (Christie 1999) has been maintained voluntarily by the participation of multiple researchers and faculty since the 1990s. The testbed datasets have been used in multiple studies by Didier et al. (2018, 2017, 2015) to evaluate the application of various seismic resilience frameworks for electrical power networks.	Christie (1999), Didier et al. (2015, 2017, 2018)
C-Town	The C-Town water distribution network is an imaginary testbed initially applied for the Battle of the Water Calibration Network (BWCN) competition and introduced in the 12th Water Distribution Systems Analysis Symposium in 2010 (Alvisi and Franchini 2011; Kim et al. 2011; Ostfeld et al. 2012). The testbed was also used for water network design optimization purposes (Creaco et al. 2014) and investigating the consequences of cyber-physical attacks on a water distribution system (Nikolopoulos et al. 2020; Taormina et al. 2016). The data files describing the C-Town water distribution network and its EPANET input files are available online in the ASCE Library (Ostfeld et al. 2012).	Alvisi and Franchini (2011), Kim et al. (2011), Ostfeld et al. (2012), Creaco et al. (2014), Taormina et al. (2016), Nikolopoulos et al. (2020)
Mesopolis	Mesopolis is a midsize virtual imaginary city created for research in water distribution systems following disaster scenarios (Johnston and Brumbelow 2008). The city has a hot and humid Texas climate and a geography layout combining aspects of the East, West, and Gulf Coast geography. A hypothetical history is assumed for mapping roads, land-use distribution, and infrastructure design purposes. The testbed's community module includes water, power, and communication network models and its hazard module consists of water contamination scenarios only (Shafiee and Zechman 2010; Shafiee and Berglund 2014; Shafiee and Zechman 2011).	Johnston and Brumbelow (2008), Shafiee and Zechman (2010, 2011), Shafiee and Berglund (2014)

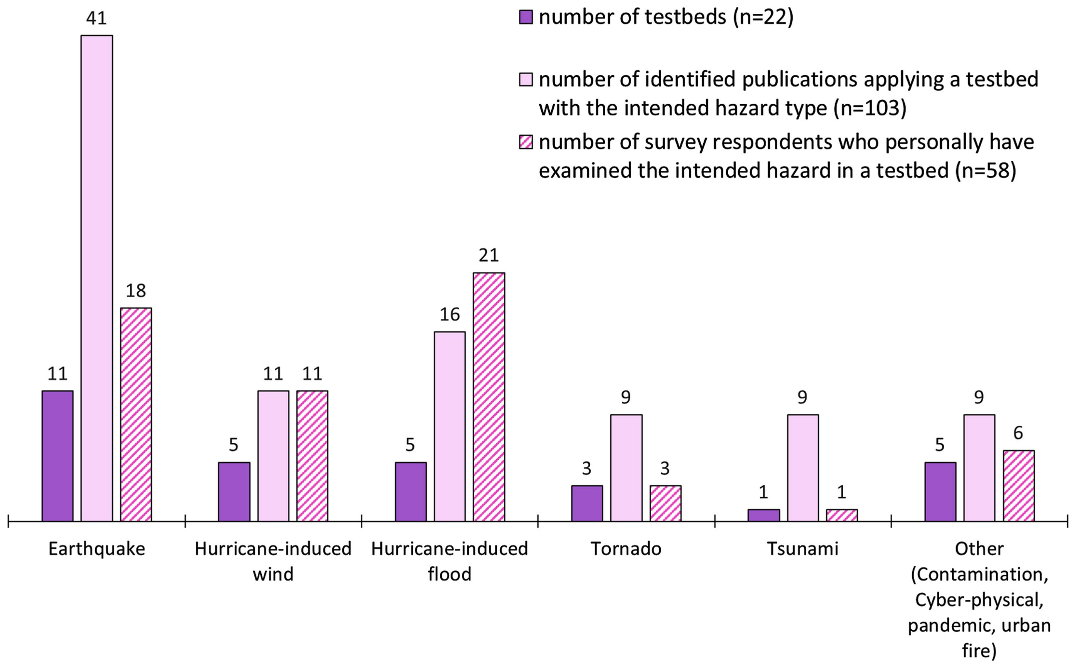

Fig. 4. Dispersion of different hazard types in the reviewed testbeds.

publications since they are modeled by more than one team of researchers, as is the case for Shelby County (Adachi and Ellingwood 2009; Chang and Shinozuka 2004; Dueñas-Osorio et al. 2007; Hwang et al. 2000; Shinozuka et al. 1998), Harris County (Dong et al. 2020a; Fan et al. 2020; Ouyang and Dueñas-Osorio 2012, 2014, 2011; Ouyang et al. 2012; Ouyang and Wang 2015), Micropolis (Bagchi 2009; Brumbelow et al. 2007), and San Francisco Bay Area (Elhaddad et al. 2019; Kiremidjian et al. 2007). Fig. 5 compares the number of testbeds modeling a particular physical system component with the number of identified publications applying that component and the number of survey respondents who indicated they personally had examined such components in a testbed. As shown in Fig. 5, the building inventory and water network are the most common components included in the modeling of the existing testbed's physical system, followed by power and transportation networks. The number of publications for testbeds with an incorporated water network is more than that of testbeds with building inventory. However, the number of expert survey respondents with personal experience of modeling a testbed's physical system using a building inventory is greater than the water network, showing a slight chance of bias in the survey results. It is also remarkable that the Harris County testbed and UW Power Systems Test Case

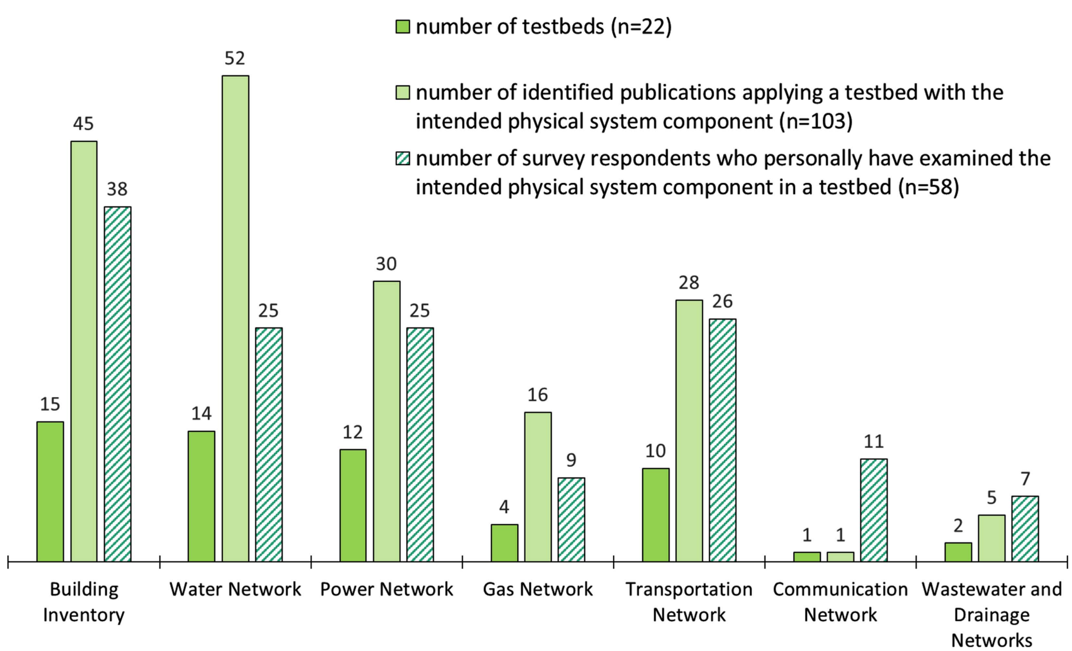

Fig. 5. Dispersion of different physical systems in the reviewed testbeds.

Archive are the only two testbeds that have not included either building portfolio or water networks in modeling the testbed's physical systems. On the other hand, the communication network is modeled in Gotham City only (Mahmoud and Chulahwat 2018).

Social and Economic Systems: Physical systems are only useful if they serve people. Thus, it is critically important to include the social and economic systems in community resilience analyses. Few testbeds incorporate predictive simulation models for social and economic systems, as opposed to static estimates of demographics, social vulnerability, or postdisaster economic impacts. The *social system* captured in existing testbeds includes one or more social models such as population evacuation (Wang et al. 2016), population dislocation (Roohi et al. 2021; van de Lindt et al. 2019), housing unit allocation (Gardoni et al. 2018), and housing recovery model (Sutley and Hamideh 2020). The *economic system* of the reviewed testbeds comprises either classic input-output impact models (Shinozuka et al. 1998), computable general equilibrium (CGE) models (Chen and Rose 2018; Cutler et al. 2016; Roohi et al. 2021), or business interruption and recovery models (Aghababaei et al. 2021; Attary et al. 2019; Watson et al. 2020; Yang et al. 2016). However, as identified in our review, most testbeds limit social and economic system consideration to socioeconomic indicators. The indicators are either a composite indicator such as the social vulnerability index (Little et al. 2020; Mahmoud and Chulahwat 2018) or a set of census data including age, race, ethnicity, housing vacancy rates, population density, the number of households, household mean annual income, owner or renter status, and the number of students and employees (Masoomi and van de Lindt 2017; Nozhati et al. 2018a; Shang et al. 2020). The degree of social and economic data and resolution of such models in a testbed, either imaginary or real, depends on the data available, and the skillset of the researchers involved with the testbed. The availability of high-resolution social and economic data is difficult to obtain and cannot be made publicly available due to ethical and security-related issues in real testbeds.

Next Steps in Testbed Development

Based on our findings from the literature review, we have identified four aspects of community resilience testbeds that warrant additional research, including (1) data needs, data collections, and data security concerns; (2) testbed visualization; (3) testbed V&V; and (4) testbed availability and reuse; each is discussed herein.

Data Needs, Data Collections, and Data Security Concerns

In the development of virtual testbeds, a major limitation is access to data due to availability, security issues, and ethical considerations, particularly as it relates to accessing and publishing data for reuse. Researchers have often resorted to modeling major simplification of real communities as testbed communities, using aggregate data, a suite of archetypes to represent all buildings in a community, and limiting the scope of their analyses. For example, roof shape is an important building attribute for testbeds with wind hazard modules but is often not provided in public data. In these cases, Artificial intelligence (AI) and computer vision methods (Wang et al. 2021) can be employed to capture the required information from Google Street View and satellite images. For example, leveraging recent developments in AI (particularly in deep learning) and computer vision techniques, Microsoft Building Footprint Database created nationwide building footprint maps (Microsoft 2020) that are very useful for community resilience testbeds. Similarly, Wang et al. (2021) developed a machine learning-based framework for generating building inventory of a community to support regional hazard analysis; the framework has been applied for the development of the Atlantic County testbed (McKenna et al. 2021).

Private data can fill these needs but sometimes can be too expensive for academic researchers and, again, cannot be published for reuse by the research community. For example, insurance data are not publicly available at a household level, and even OpenFEMA data is aggregated to the zip code level. Without access to high-resolution social and economic data, those types of systems will always lag behind physical models in testbed development.

The other challenge that testbed developers encounter is merging different datasets with different spatial and temporal units. For example, Building Footprint, Land Use, and Tax Parcels are the common public datasets that are used for compiling the building inventory of a testbed. However, each of these datasets uses different identifiers, including individual building, map block number, and parcel number, respectively. Additionally, different data sources generate their data differently and handle missing data differently. For example, McKenna et al. (2021) reported that Microsoft Footprint Database sometimes lumps the footprints of closely spaced buildings together.

Testbed Visualization

Any geographic information system (GIS) software can be used to visualize a testbed. The GIS provides the opportunity to integrate both the attribute and spatial data for all of the components in a testbed's community module to be stored in a single database. The community resilience analysis outcomes can also be mapped into GIS. The ESRI ArcGIS and Q-GIS are the most popular software for testbed visualization but require other software to chain algorithms and simulate disasters. Open-source libraries, such as Leaflet and Folium, are also recently used widely to visualize testbed interactively in Python environments.

Testbed Verification and Validation

The process of V&V of testbeds is an important step to be able to apply results from a testbed analysis to the real world. This is a challenging process that is often considered but not fully discussed in publications. Such a complex computational environment must be validated with each component being verified as a single or integrated module or system. The accuracy of the data (particularly the public data) that are used for the testbed creation can initially be verified using online tools and comparing the mutual attributes between datasets from different resources. For example, in the San Francisco testbed, Elhaddad et al. (2019) verified the accuracy and quality of UrbanSim datasets by comparing its information on location and building geometry with the Microsoft Building Footprint database. After verifying the accuracy of integrated datasets, the testbed's numerical simulation models should be validated to ensure that it results in the desired outputs. There are various existing techniques to verify and validate a testbed. In the CLARC testbed, the V&V were performed by involving stakeholders and local experts in comparison between the analysis results and past storm events (Loggins and Wallace 2015). Attary et al. (2019) and van de Lindt et al. (2019) used the building damage assessment report of the Joplin 2011 tornado as well as power outage reports by the residents after the tornado to validate their testbed model. Even if an individual researcher validates their model contributions, as testbeds grow and expand, who performs validation and how will remain an important challenge.

The expert survey asked, "Are you aware of, or did you perform, any validation of the testbed(s) you used?" and gave additional guidance that "Validation could have consisted of testing accuracy of

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assets, locations, properties, matching information to prior events, etc." It should be noted that besides the importance of a testbed's V&V itself, the documentation of the V&V process and making the documentation of the V&V process available to testbed's users are two essential steps in a testbed's development process to make the testbed functional for researchers other than the testbed's development team. 51 responses were recorded to this question, where 32 reported YES and 19 reported NO, which illuminates that almost 37% of respondents neglected this important step. Of the 32 respondents indicating they had performed or were otherwise aware of validation of the testbed(s), 28 provided comments. Through the comments, 15 validated results using postdisaster data; 5 used expert knowledge, 8 used other secondary data comparisons, such as census data and google maps; 2 performed sensitivity analysis; and 3 made a comparison with other published work. This provides a guide for how future testbed developers and users can verify and validate their work.

Testbed Availability and Reuse

After the creation of a testbed, most testbeds are reused by the researchers who created them. At this time, testbeds are not frequently reused by other researchers, but through the creation of recent platforms such as DesignSafe-CI and IN-CORE, datasets can be shared and used by others. Data collection and validation are extensive and time-consuming processes. The sharing and reuse of testbeds that have already been verified and validated push forward the progress of community resilience research.

Conclusions

Virtual testbeds are being developed and used across the community resilience literature to serve the purpose of V&V. We identified 22 community resilience testbeds and 103 publications that use community resilience testbeds. There is no shortage of testbeds, but their accessibility for use by the research community and availability of their development documents remains a major challenge. There is no apparent standardized process for testbed development, testbed publication, or testbed reuse. It is no trivial effort to develop a testbed, including obtaining and cleaning data, developing, validating, and chaining algorithms, and verifying simulation results. Such standardizations may help improve the accessibility of testbeds to the research community, which can have important implications for advancing knowledge on community resilience analysis where every next researcher does not have to reinvent the wheel by developing a new testbed. A secondary outcome of this review is to aid interdisciplinary teams of hazards and disasters researchers in working together on testbeds and in understanding where the state of knowledge is on testbed development.

Community resilience testbeds should have both a hazard module and a community module. Ideally, the community module in a fully developed testbed includes one or more interconnected models of the desired community's physical, social, and economic systems; however, only one of the three is required to *initiate* a testbed. The concept of virtual community resilience overlaps with some common classic risk assessment tools or modern high-tech simulation instruments such as a digital twin. However, these tools do not meet the proposed definition of the testbeds and do not provide the required architecture and ample metadata that testbeds are supposed to provide.

Aside from the fact that none of the existing testbeds are fully developed, the majority of them have been created with a focus on earthquake hazards and physical infrastructure systems. Even if a testbed intends to include social and economic systems, these models are primarily population-based, and the other dimensions of the social and economic systems, such as social services and organizational preparedness, are consistently overlooked. This leads to ample opportunity to advance knowledge with other hazard types, and social and economic systems, which requires multi-, inter-, and transdisciplinary collaborations.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available in a repository or online in accordance with funder data retention policies. The expert survey results, instruments, and reports that are referred to in this study are available in the DesignSafe-CI data repository at https://doi.org/10.17603/ds2-9w9v-my55.

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